Overview of Progress in Neutrino Scattering Measurements

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Scope and Cautionary Remarks

Scope

Review progress in neutrino scattering measurements since NuInt01. Focus on:

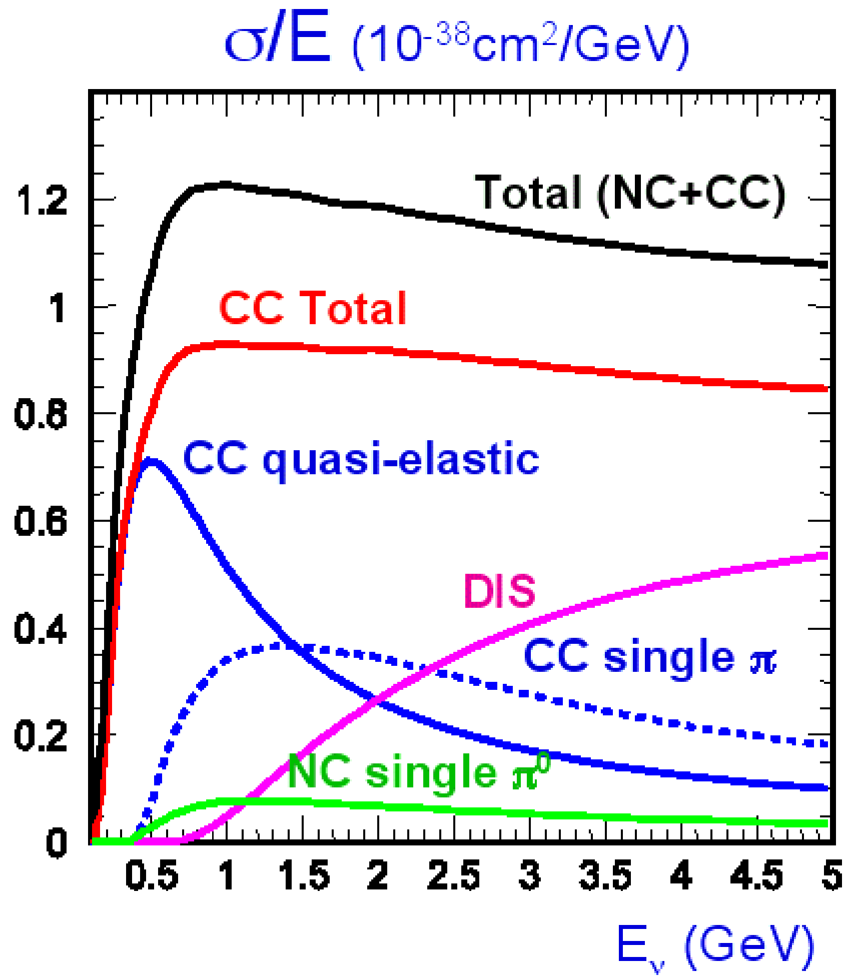
- 0.1 < E_ν (GeV) < 10 neutrino energy range
- Neutrino rather than charged lepton (*B. Bradford's talk, this session*) or pion/proton scattering data
- Recent data rather than recent development on neutrino scattering modeling (*C. Andreopoulos' talk, this session*)

Cautionary Remarks

- many of the results that will be shown are still preliminary and may change (starting from NuInt07!) in the future. Those are marked with P throughout the talk
- direct comparisons between experiments are sometimes difficult. Tried to be explicit about assumptions used

Outline

- Neutrino experiments reporting recent progress
- Quasi-elastic scattering
- Resonant Pion Production
- Coherent Pion Production
- From resonance to DIS region
- Nuclear effects
- Future



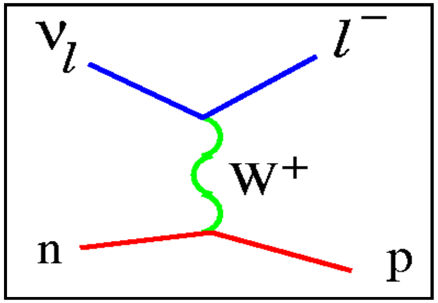
Source: NEUT, NuInt05

Neutrino Experiments Reporting Recent Progress

- *K2K near*:
  - *1KT* (Cherenkov detector, water target, ~10^5 interactions)
  - *SciFi* (segmented tracker, water, ~10^4 interactions)
  - *SciBar* (segmented tracker, carbon, ~10^4 interactions)
- *MiniBooNE* (Cherenkov, mineral oil, ~10^6 interactions)
- *NOMAD* (spectrometer/calorimeter, carbon, ~10^6 interactions)
- *MINOS* near (magnetized tracking calorimeter, iron, ~10^6 interactions)
- *Lar50* (Lar TPC, Ar, ~10^4 interactions)
- Reanalyses of *BNL-7ft* + *GGM* data (bubble chambers, deuterium and propane/freon, ~10^3 interactions)

See Session 3 talks for details on most of these

Quasi-Elastic Scattering



- Llewellyn Smith formalism:

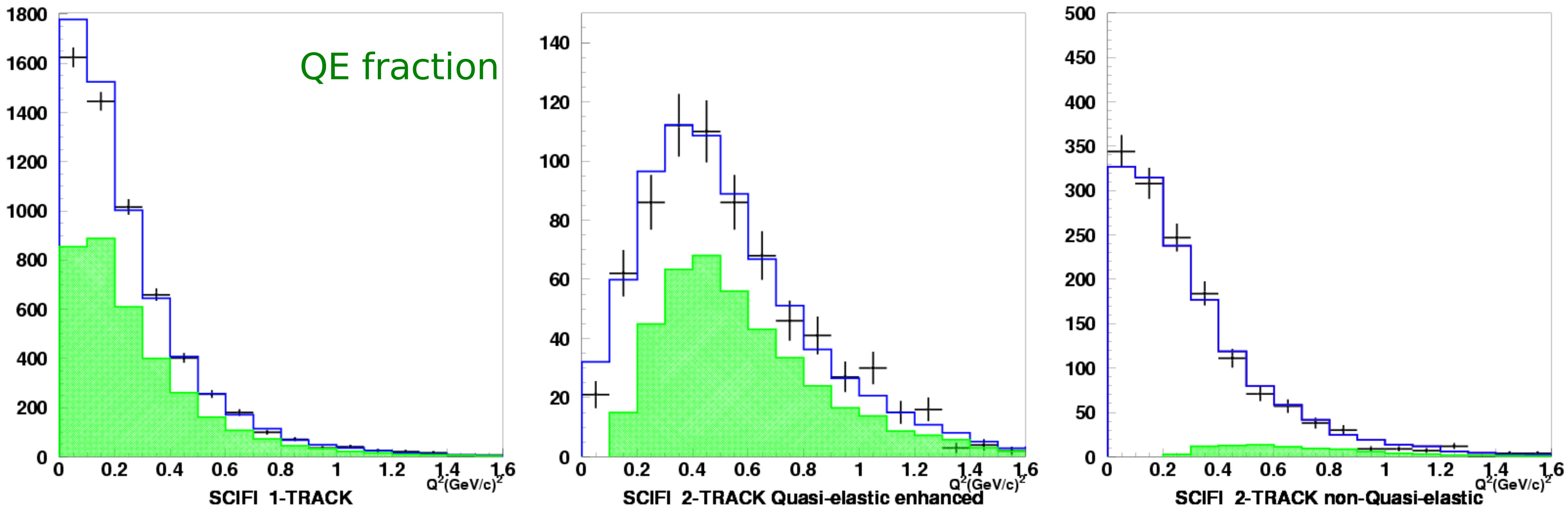
$$\frac{d\sigma}{dQ^2} = \frac{m_N^2 G_F^2 |V_{ud}|^2}{8\pi(\hbar c)^4 E_\nu^2}\left[A(Q^2) \pm B(Q^2)\frac{(s-u)}{m_N^2} + \frac{C(Q^2)(s-u)^2}{m_N^4}\right]$$

- (s-u) ~ $4m_N E_\nu - Q^2$
- + for neutrinos, - for antineutrinos
- A,B,C depend on two vector (f_1, f_2) and one axial vector (g_1) form factors
- Q^2 dependence of axial vector form factor assumed to have dipole form:

$$g_1(Q^2) \approx \frac{1.25}{(1+Q^2/m_A^2)^2}, \quad m_A\text{: axial mass}$$

- Vector form factors: few % deviations from dipole form from electron scattering data (*-> B. Bradford, this session*), causing few % differences in CCQE cross section and axial mass extraction in recent analyses

K2K-SciFi MA Result



Source: PRD 74, 052002 (2006)

- Fit shape of Q^2 distribution in 1 track and 2 track QE-enriched CC samples
- Include 2 track nonQE-enriched CC sample to constrain background normalization
- Fit Q^2 in separate E_ν bins to constrain flux predictions
- Fit only Q^2 > 0.2 GeV^2 region to avoid large uncertainties due to nuclear effects
- Total sample ~ 7,000 events
- Axial mass result: **M_A = (1.20 ± 0.12) GeV**

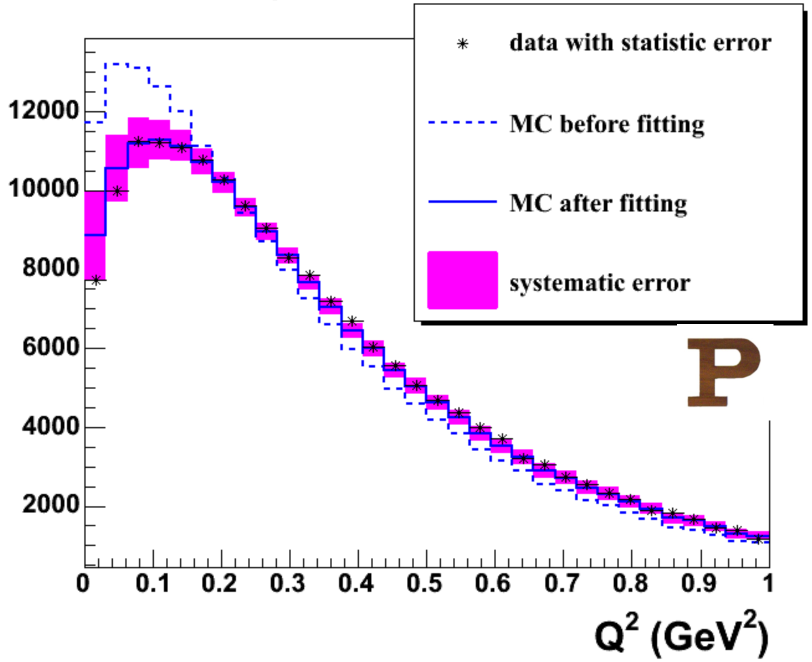
Preliminary MiniBooNE CCQE

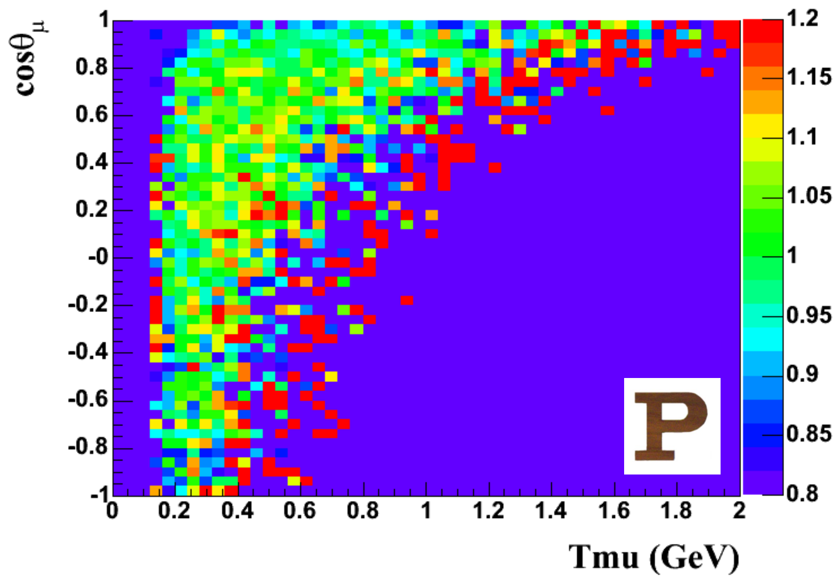
- Preliminary axial mass result: **M_A = (1.22 ± 0.10) GeV**
  Since then, analysis has been updated

(Source: J. Monroe, Columbia U. Ph.D. thesis, 2006)

- CCQE selection: contained CC events with single decay electron tag, correlated in space with muon track endpoint. 200,000 events with ~74% estimated CCQE purity
- Fit shape of Q^2 distribution, to measure both:
  - Axial mass
  - Parameter controlling strength of Pauli suppression in relativistic Fermi gas model
- Achieve good data/MC agreement in CCQE kinematic distributions after tuning these two parameters in MC

(Source: J. Conrad, B. Louis, FNAL Seminar, April 2007)





NOMAD CCQE Cross Section

- Select CCQE events in $3 < E_\nu < 100$ GeV range by requiring:
  - *Two tracks, one identified as μ^-, other consistent with proton*
  - *Invariant hadronic mass: $W < 1.76$ GeV^2*
  - *CCQE-like rather than background-like (RES, DIS) events, based on 3D likelihood*
  - ~8,000 events, with ~71% estimated purity

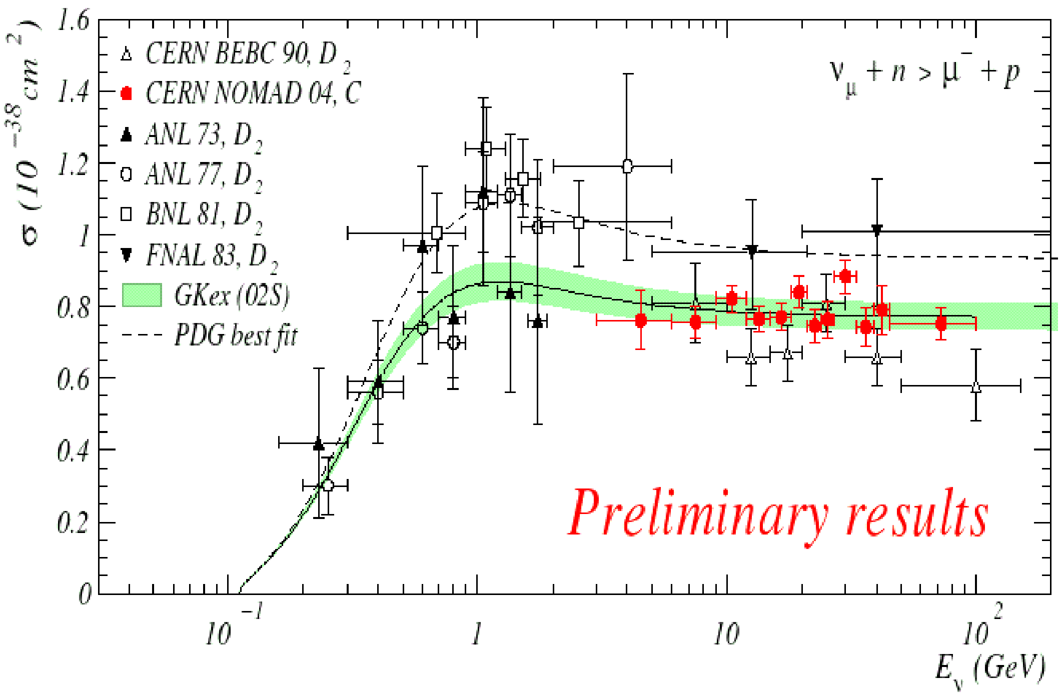
- Normalization via DIS sample in $40 < E_\nu < 200$ GeV, whose cross section is taken as $\sigma / E_\nu = 0.677 \cdot 10^{-38}$ cm^2 / GeV

- Preliminary CCQE cross section: **$\sigma(\nu_\mu n \rightarrow \mu^- p) = (0.72 \pm 0.01)\ 10^{-38}$ cm^2**

- Error quoted is statistical-only

- Systematic uncertainty evaluation underway, expected to be dominated by nuclear effects

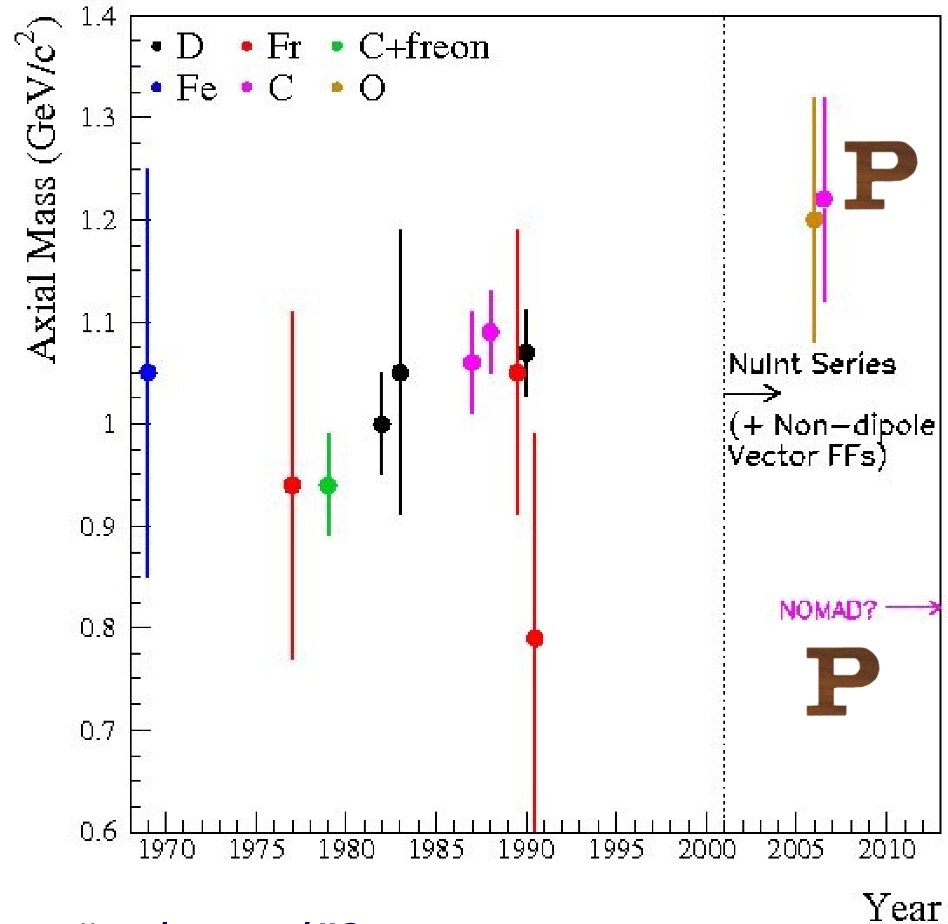
- Measured cross section is ~20% smaller than the world average of previous bubble chamber experiments



(Sources: R. Petti, Nuint05; V. Lyubushkin and B. Popov, Phys. Atomic Nucl. 69, 1876 (2006))

Quasi-Elastic Progress Since NuInt01

- Recent CCQE models now typically use non-dipole vector form factors from electron scattering data, affecting at few % level MA extraction
- Given current accuracy, dipole approximation for axial FF seems OK
- MA values from recent Q^2 shape analyses (K2K-SciFi, prelim. MiniBooNE) are consistent with each other, but higher than historical world average
- Prelim. NOMAD CCQE cross section, using different method (DIS normalization), seems to suggest much lower MA values. Need to wait for full systematic error evaluation

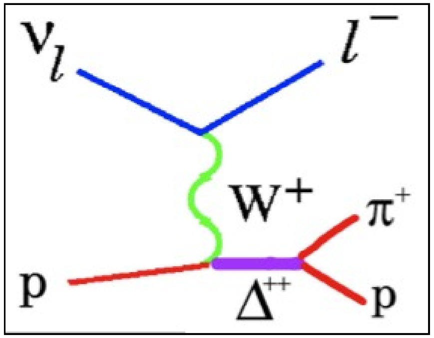


-> experimental biases, or MA parameter is not "universal"?

Look forward to new NuInt07 CCQE and NC elastic results (Session 5):

- F. Sanchez, *"K2K QE Results from SciBar"*
- T. Katori, *"Charged-Current Interaction Measurements in MiniBooNE"*
- C. Cox, *"MiniBooNE NC-E Interactions"*

Resonance Production



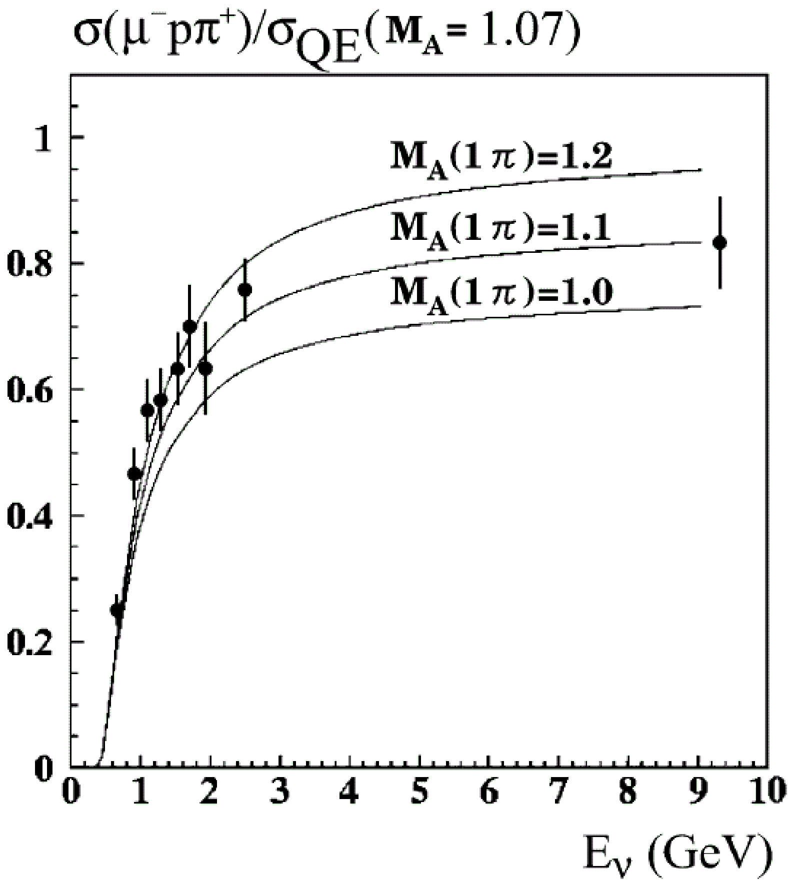
- Single pion production via excitation, and subsequent decay, of resonances of hadronic masses 1.08 < W (GeV) < 1.4-2.0
- 14 final states overall (6 CC, 8 NC):

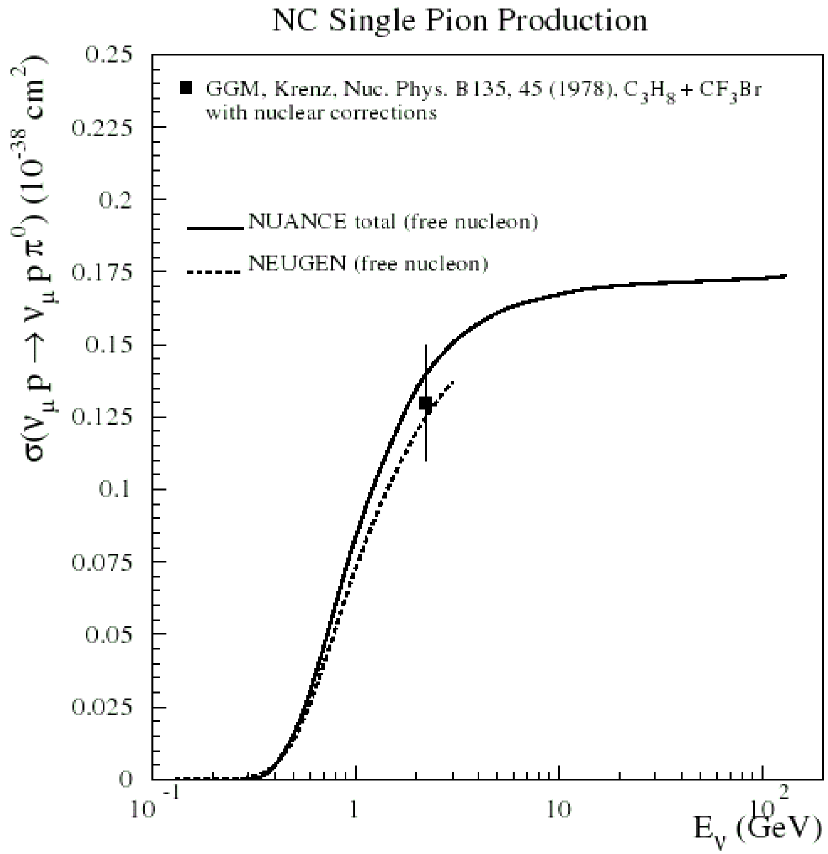
CC		NC	
$\nu_\mu p \to \mu^- \Delta^{++}$	$\Delta^{++} \to p\pi^+$	$\nu_\mu p \to \nu_\mu \Delta^+$	$\Delta^+ \to p\pi^0, \Delta^+ \to n\pi^+$
$\nu_\mu n \to \mu^- \Delta^+$	$\Delta^+ \to p\pi^0, \Delta^+ \to n\pi^+$	$\nu_\mu n \to \nu_\mu \Delta^0$	$\Delta^0 \to n\pi^0, \Delta^0 \to p\pi^-$
$\overline{\nu}_\mu p \to \mu^+ \Delta^0$	$\Delta^0 \to n\pi^0, \Delta^0 \to p\pi^-$	$\overline{\nu}_\mu p \to \overline{\nu}_\mu \Delta^+$	$\Delta^+ \to p\pi^0, \Delta^0 \to n\pi^+$
$\overline{\nu}_\mu n \to \mu^+ \Delta^-$	$\Delta^- \to n\pi^-$	$\overline{\nu}_\mu n \to \overline{\nu}_\mu \Delta^0$	$\Delta^0 \to n\pi^0, \Delta^0 \to p\pi^-$

- Rein and Sehgal formalism. Resonance production and decay matrix elements computed according to FKR model and resonance decay experimental input
- Transition form factor appearing in production amplitude:

$$G_A(Q^2) \approx (1+Q^2/(4\mathrm{m}_N^2))^{1/2-n} \frac{1}{(1+Q^2/m_A^2)^2}, \quad m_A: \text{single pion axial mass}$$

Reanalyses of Bubble-Chamber Data





- BNL-7ft $\nu_\mu p \to \mu^- p \pi^+$ data (~3,000 evts.)
- Good agreement found with R-S model

(Source: K. Furuno, NuInt02)

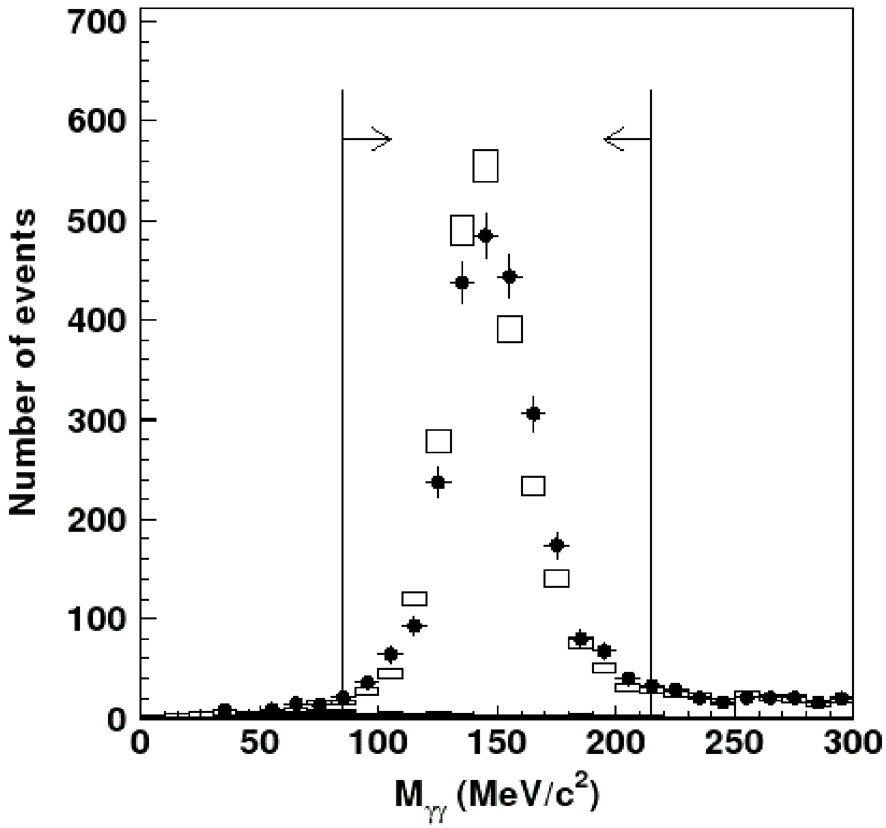
- ANL data also reanalyzed and compared to R-S

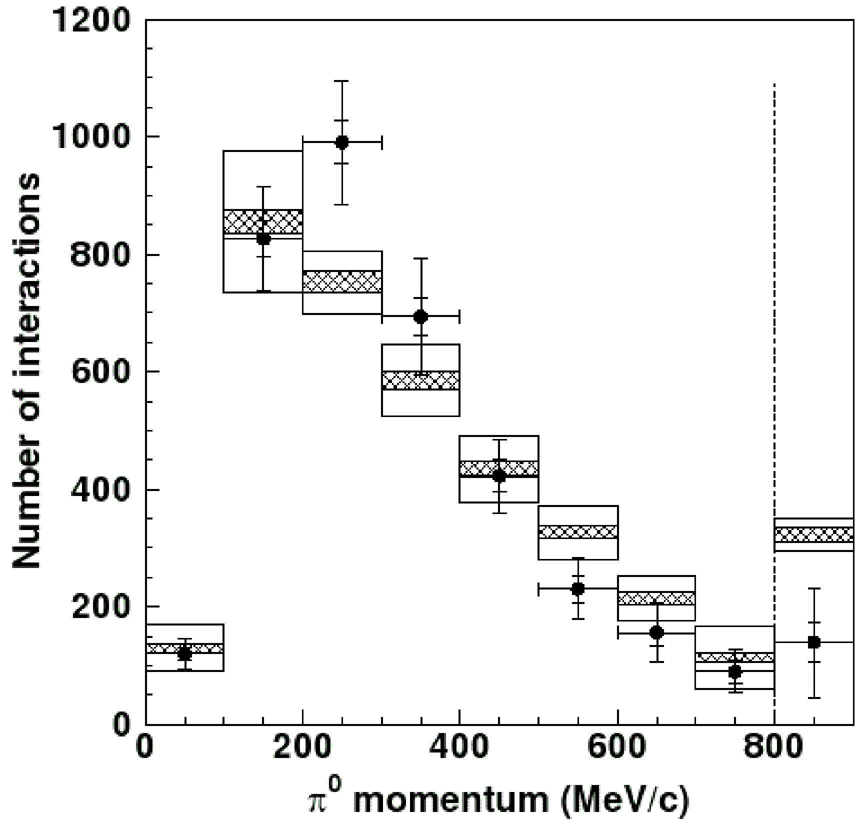
- Reanalysis of GGM $\nu_\mu p \to \nu_\mu p \pi^0$ data (~200 evts.) to extract absolute xsec

(Source: E. Hawker, NuInt02)

- Good agreement found with R-S
- First absolute xsec measurement of NC π^0 production at low energies

K2K-1KT NC Pi0 Production





- Two e-like rings, 85-215 MeV invariant mass, ~2,500 events with ~71% purity
- Fully corrected π^0 momentum distribution, normalized to fully contained sample, shows reasonable agreement with predictions
- NC π^0 production cross section normalized to CC one:

σ(NC π^0)/σ(CC) = (0.064 ± 0.001 ± 0.007) at E_ν ~ 1.5 GeV

(Source: Phys. Lett. B619, 255 (2005))

MiniBooNE NC Pi0 Production

• Preliminary resonant NC π^0 production cross section:

$\sigma(\nu_\mu N \rightarrow \nu_\mu N\pi^0) = (1.28 \pm 0.11 \pm 0.43)\ 10^{-38}\ cm^2/CH_2$,at E_ν~1.3 GeV and flux extracted via CCQE sample

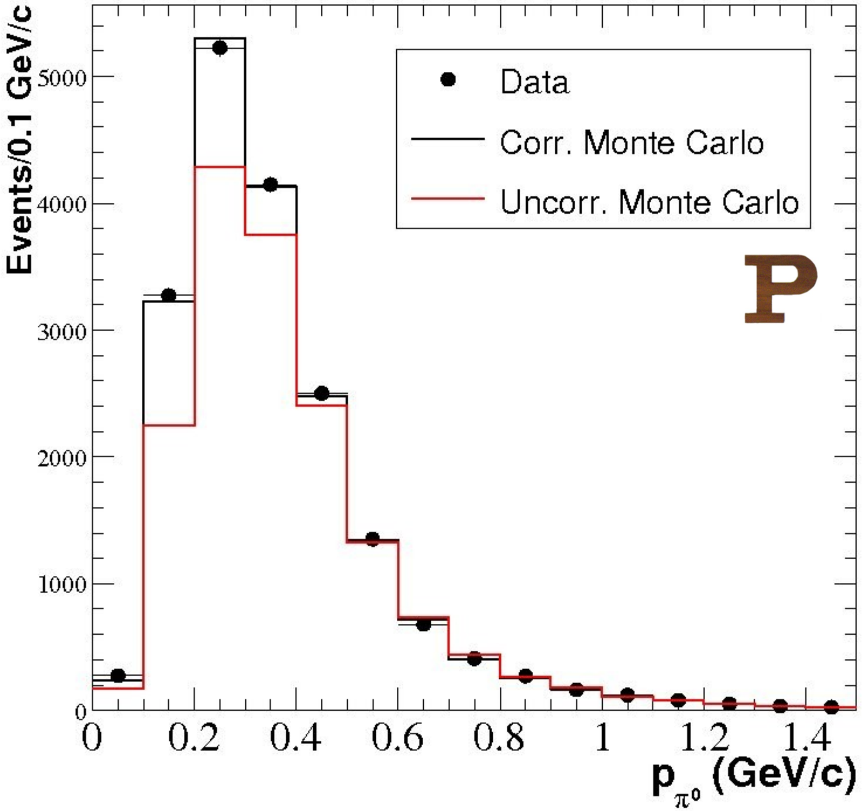
(Source: J. Raaf, U. of Cincinnati Ph.D. thesis, 2005)

• Analysis updates since then on reconstruction, optical model, selection

• No decay electrons, e/μ and e/π^0 likelihood ratios favor e and π^0 hypotheses, respectively, $80<m_{\gamma\gamma}<200$ MeV

• ~20,000 events with >90% purity

• Default Monte Carlo underpredicts π^0 production rate at low π^0 momenta, but overall not bad

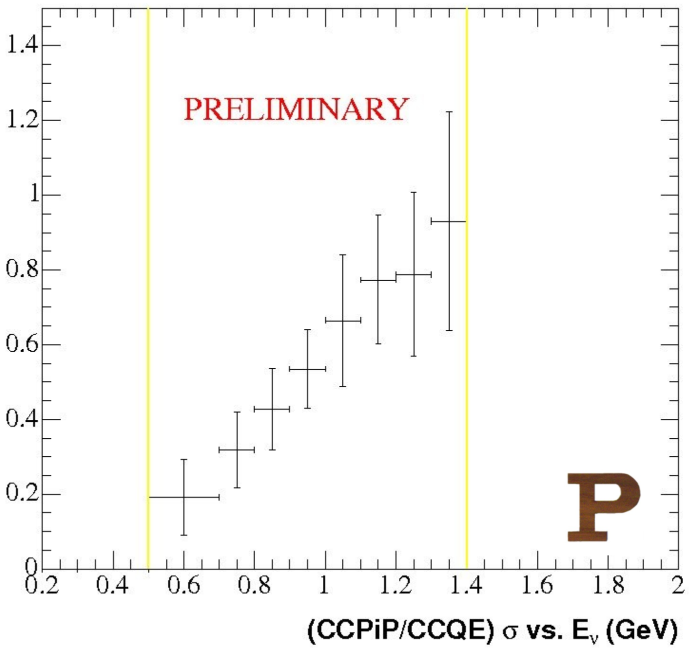


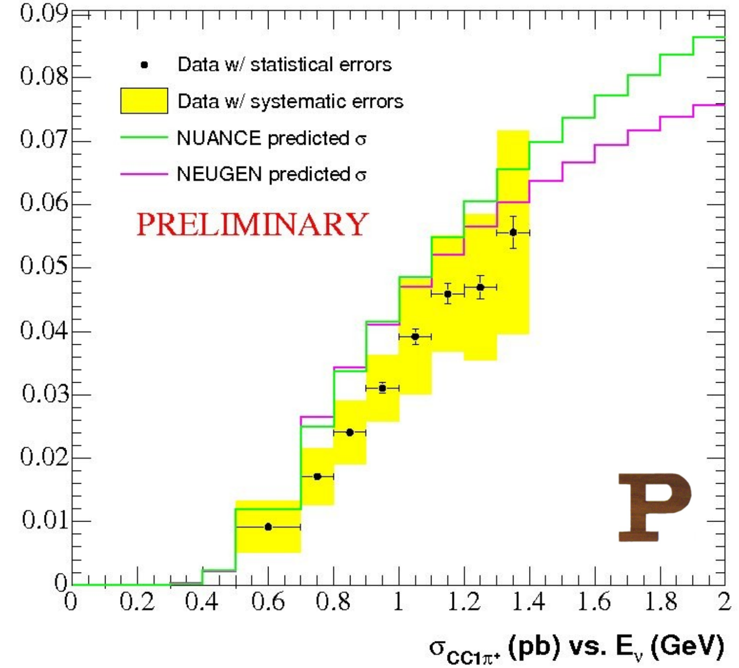
(Source: J. Conrad, B. Louis, FNAL Seminar, April 2007)

MiniBooNE CC Pi+ Production

- Select $\nu_\mu N \rightarrow \mu^- N \pi^+$ events by requiring two decay electrons from $\mu^- \rightarrow e^-$ and $\pi^+ \rightarrow \mu^- \rightarrow e^-$ decays. ~44,000 events ($3.3 \cdot 10^{20}$ pot), ~85% purity
- Neutrino energy from muon kinematics, assuming $m(\Delta) = 1.23$ GeV resonance
- Normalize corrected $CC\pi^+$ rate to CCQE one, to extract cross section ratio
- Get $CC\pi^+$ cross section by multiplying by NUANCE CCQE cross section prediction (M_A=1.03 GeV). ~25% lower than predictions, but comparable uncertainties

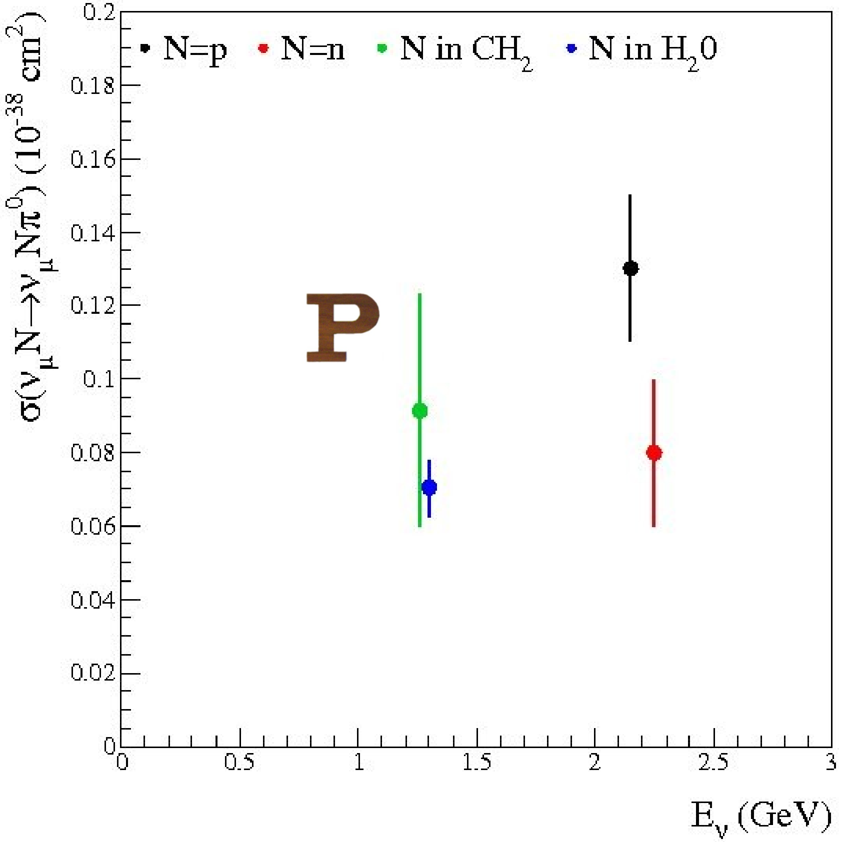
(Source: M. Wascko, NuInt05)





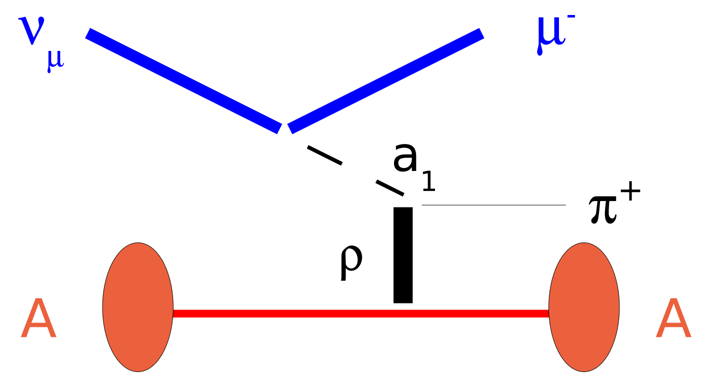
Resonance Production Progress Since NuInt01

- A lot more data, clear example being NC π^0 production shown here, for which we had no absolute xsec measurement before NuInt01
- Three recent results, reasonably consistent with each other:
  - reanalysis of GGM data (black, red)
  - $\sigma(\text{NC } \pi^0)/\sigma(\text{CC})$ from K2K-1KT, multiplied here by NEUT CC xsec prediction (blue)
  - preliminary MiniBooNE resonant NC π^0 xsec, with flux extraction via CCQE sample assuming MA=1.03 GeV (green)



- High statistics samples allow us to test in detail for the first time pion production kinematics. Our current modeling seems OK at the ~20% level
- Look forward to new NuInt07 resonant pion production results (Session 6):
  - J. Link, *"Neutral Current pi0 Production at MiniBooNE"*
  - B. Fleming, *"Charged Current pi+ Production at MiniBooNE"*
  - L. Whitehead, *"Charged Current pi+ Production at K2K"*
  - C. Mariani, *"Neutral Pion Production Cross Sections at K2K"*

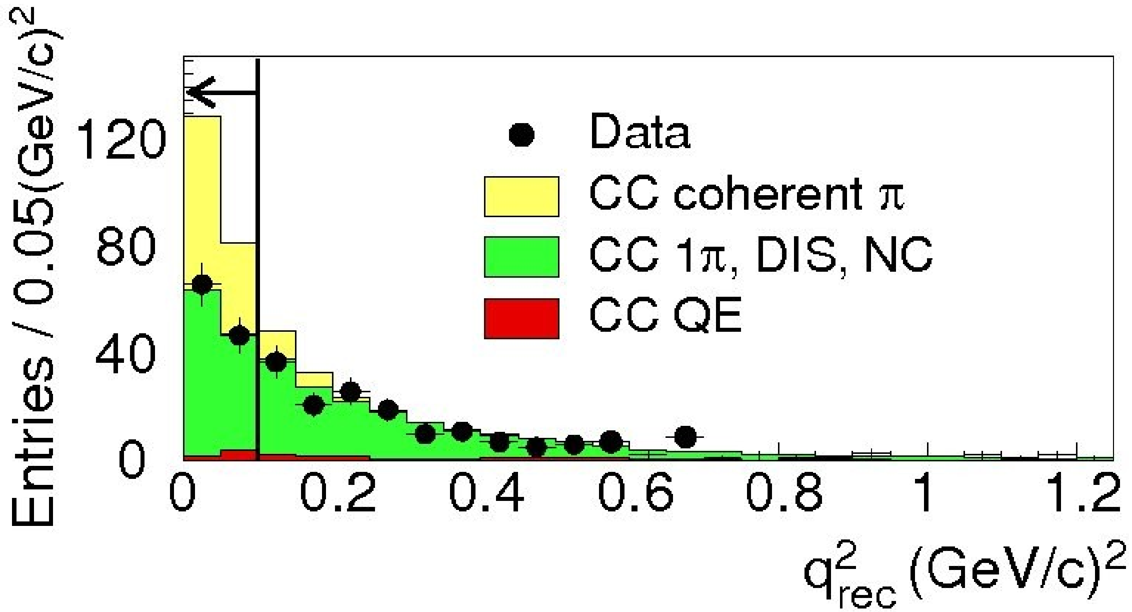
Coherent Pion Production



- Neutrino interacts coherently with nucleons bound in the nucleus, producing a pion
- Cross section expected to be smaller (up to ~20% for E_ν~1 GeV) than resonant pion production, but with distinct signature:
  - forward-scattered pion
  - no nuclear break-up
- Both CC and NC modes possible: **$\nu_\mu A \to \mu^- A \pi^+$, $\nu_\mu A \to \nu_\mu A \pi^0$**
- Neutrino and antineutrino coherent cross sections expected to be similar
- Theoretical models vary, but share general ideas:
  - Built on the basis of Adler's theorem, relating neutrino-nucleus cross section to pion-nucleus one, at $Q^2=0$
  - Extrapolation to $Q^2 \neq 0$ via propagator term governed by coherent axial mass, $M_A \sim$ 1-1.35 GeV

K2K-SciBar CC Coherent Pi+ Production

- Select CC coherent pion candidates with ~47% expected purity by requiring:
  - CC interaction with 2 tracks, one muon and one π^+-like track
  - low vertex activity
  - low momentum transfer: Q^2<0.1 GeV^2
- Use control samples to tune momentum scale, nQE/QE ratio, strength of nuclear effects
- 113 events selected, consistent with background-only



- Upper limit (90% CL) on CC coherent pion cross section normalized to CC inclusive:

σ(CC coh π)/σ(CC) < 0.60·10^{-2}

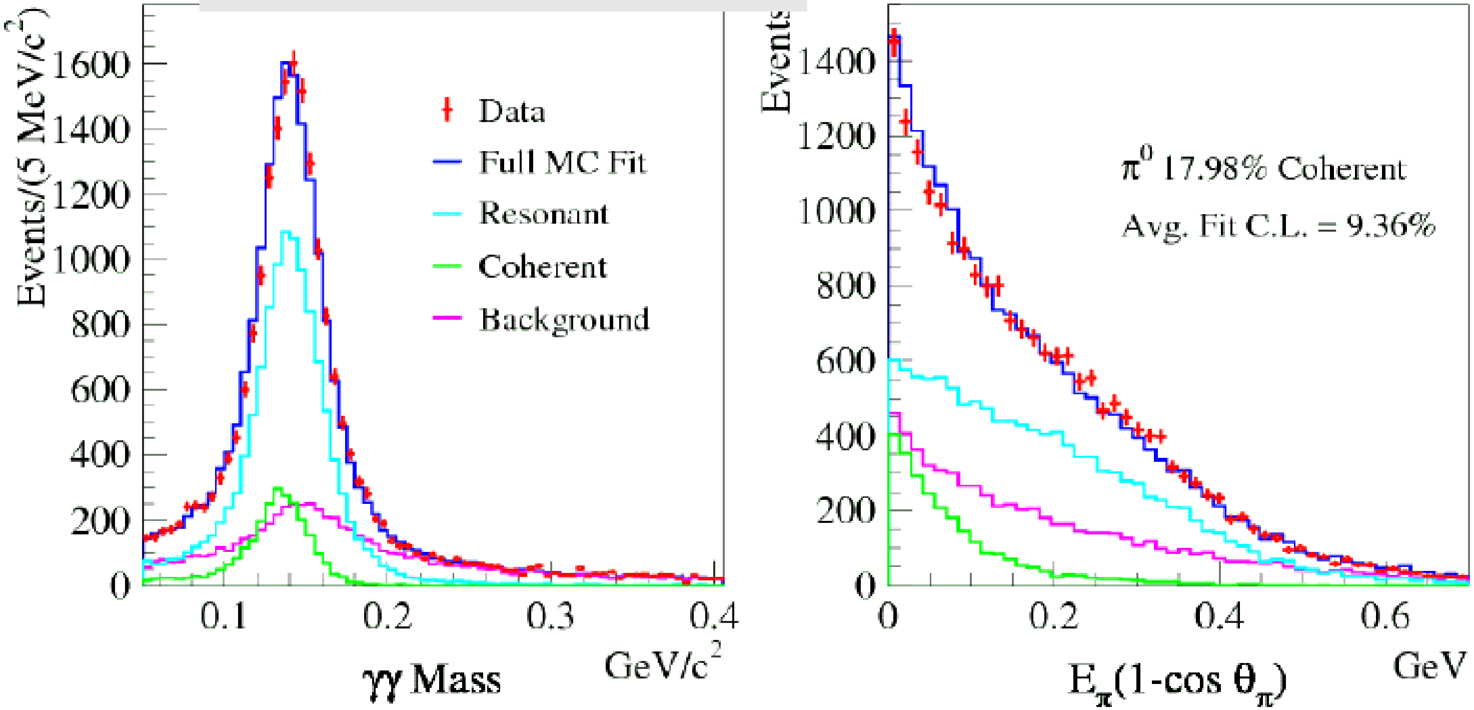
at E_ν ~ 1.3 GeV

(Source: Phys. Rev.Lett. 95, 252301 (2005))

MiniBooNE NC Coherent Pi0 Production

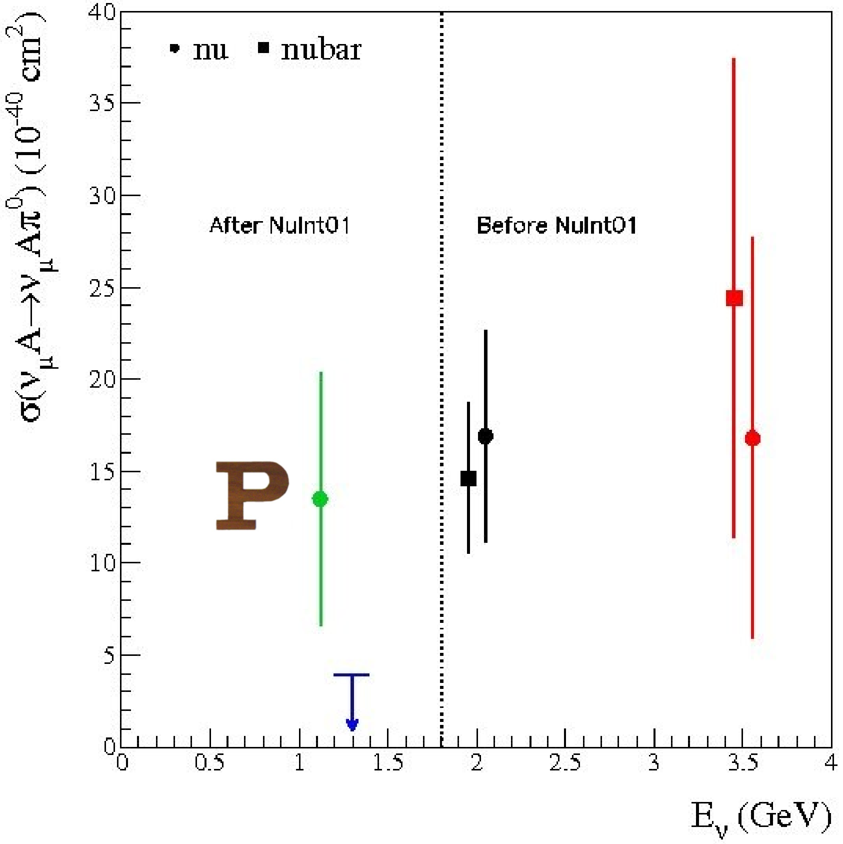
- Select ~30,000 events by requiring no decay electrons, e/μ and e/π^0 likelihood ratios favor e and π^0 hypotheses, respectively, $m_{\gamma\gamma} > 50$ MeV
- Perform 2D fit in $m_{\gamma\gamma}$ and $E_\pi(1-\cos(\theta_\pi))$ variables to extract coherent, resonant, background fractions in the sample
- Monte Carlo fit templates reweighted according to π^0 momentum distribution measured in NC π^0 rate analysis discussed earlier
- Coherent fraction: **$N(\text{coh } \pi^0) / (N(\text{coh } \pi^0) + N(\text{res } \pi^0)) = (18.0 \pm 1.2 \pm 1.0)\%$** at $E_\nu \sim 1.1$ GeV

(Source: J. Link, NuFact06)



Summary of Coherent Pion Production Since NuInt01

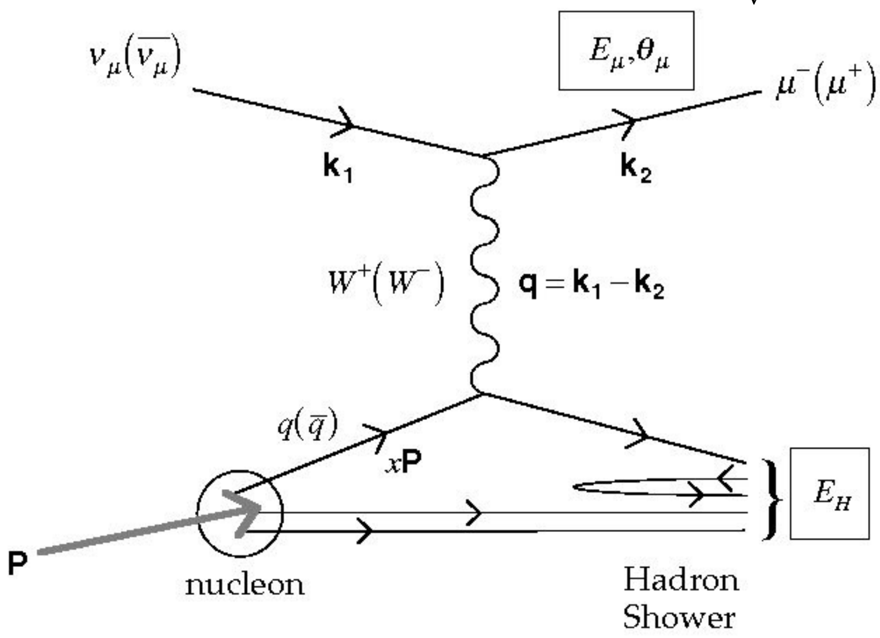
- Two new low-E results, including first CC result
- Plot shows both NC and CC coherent cross sections normalized to NC and carbon, assuming $\sigma(A)=A^{2/3}\sigma(N)$ and $\sigma(CC)=\sigma(NC)/2$
- Aachen (A~27) nu/nubar NC data (black)
- GGM (A~30) nu/nubar NC data (red)
- K2K-SciBar nu CC data (blue)
- MiniBooNE nu NC data from prelim. resonant xsec measurement (2005) and prelim. coherent fraction measurement (2006) (green)



- Tension between MiniBooNE observation and K2K-SciBar upper limit?
- More experimental input necessary to guide theory: many models on the market, yielding very different predictions
- Look forward to new NuInt07 coherent pion production results (Session 6 and poster):
  - J. Link, *"Neutral Current pi0 Production at MiniBooNE"*
  - V. Nguyen, *"Angular Dependence of pi0 Production in the MB Antineutrino Data"*

From Resonance Region to Deep Inelastic Scattering

- DIS: dominant process for E_ν>3 GeV. Allows to probe nucleon structure



- Measure E_μ, θ_μ, E_H
- *Momentum transfer*: $Q^2 = 4E_\nu E_\mu \sin^2(\theta_\mu/2)$
- *Bjorken scaling variable:* $x = Q^2 / (2ME_H)$
- *Inelasticity:* $y = (E_H - M) / E_\nu$
- *Hadronic mass:* $W^2 = M^2 + 2ME_H - Q^2$

- Differential neutrino cross sections $d^2\sigma/(dxdy)$ can be expressed in terms of structure functions $F_2(x,Q^2)$, $xF_3(x,Q^2)$, and $R_L(x,Q^2)$

- Smooth transition from resonance production to DIS regime via Bodek-Yang duality model, tuned to data in low-Q^2 overlap region

- Neutrino generators simulate low multiplicity hadronic final states up to some W~1.4-2 GeV with resonance formalism, turn to DIS formalism for higher W

MINOS Near DIS Distributions

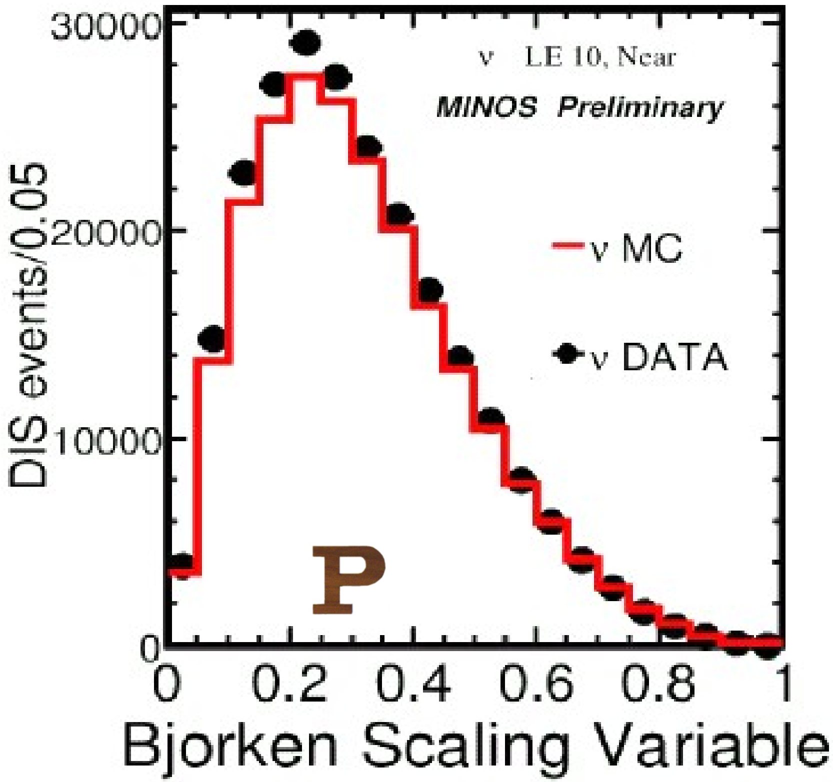
- Large data sample of DIS (W>2 GeV) and transition region (1.4<W<2 GeV) events

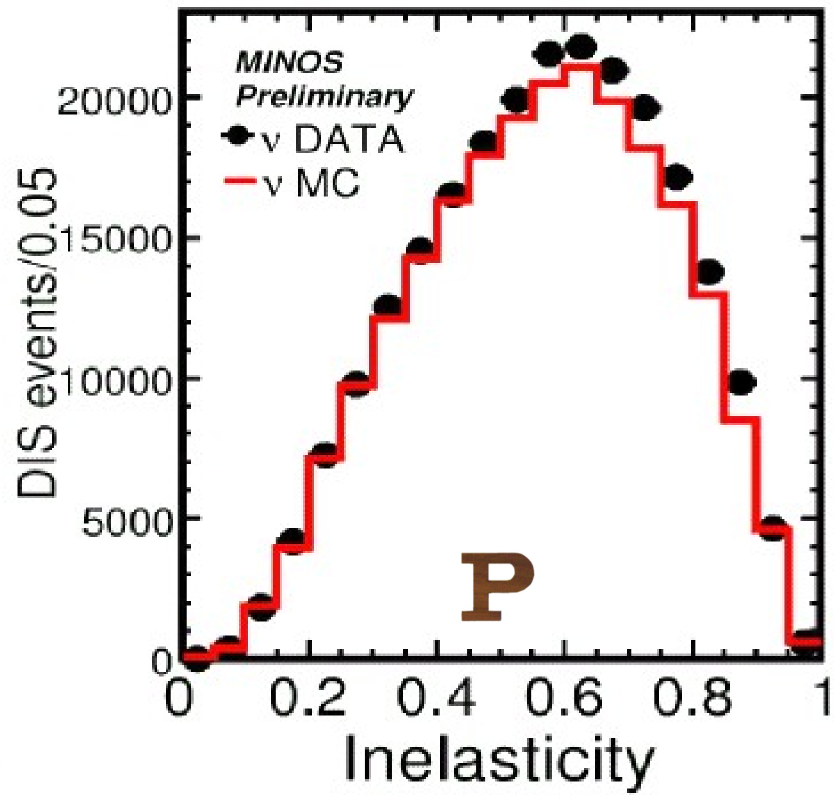
ν DIS sample:

(1E20 POT LE-10)

MC: Low-ν flux rewt.

$W > 2\,\mathrm{GeV}$
$Q^2 > 1\,\mathrm{GeV}^2$
$E_\nu > 5\,\mathrm{GeV}$





(Source: D. Naples, APS-DPF 2006)

- Require $E_H = \nu < 1$ GeV, and extract flux for $E_\nu > 5$ GeV
- From flux and event distributions, get $d^2\sigma/(dxdy)$ for neutrinos and antineutrinos

-> *extract F2 and xF3 in neutrino-iron scattering*

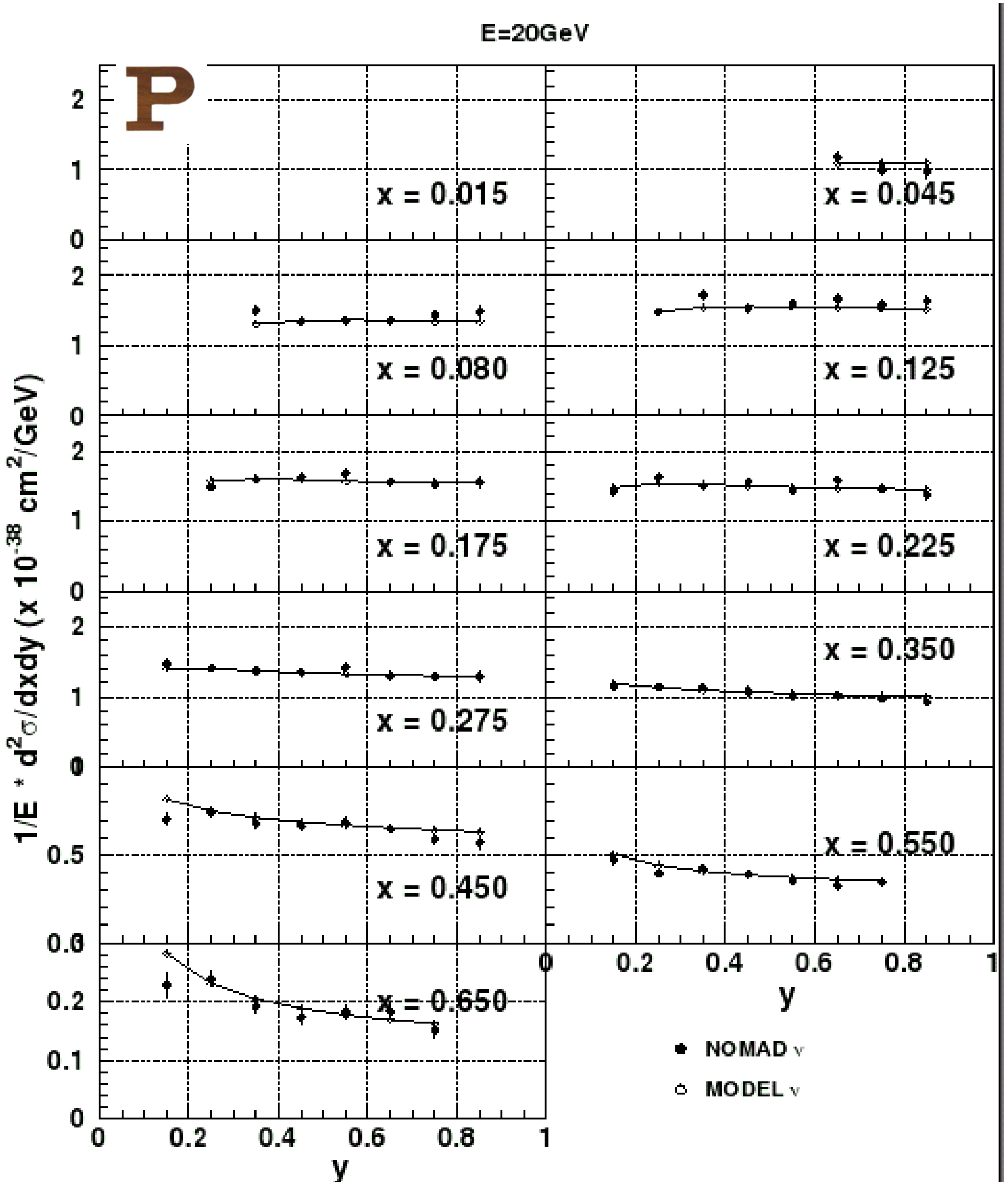
NOMAD/NuTeV Differential Cross-Sections

- Measure the CC differential cross section in ν-C interactions for $6<E_\nu<300$ GeV, by requiring:
  - μ-ID, $E_\mu > 2.5$ GeV
  - $E_H > 3$ GeV
  - $Q^2 > 1$ GeV^2
- Absolute xsec normalization from world average in $40 < E_\nu < 200$ GeV
- Measurement in (E_ν,x,y) bins, values corrected for bin centering
- First measurement of inelastic CC cross section on a carbon target and large Q^2 (~13 GeV^2)

(Source: R. Petti, NuInt05)

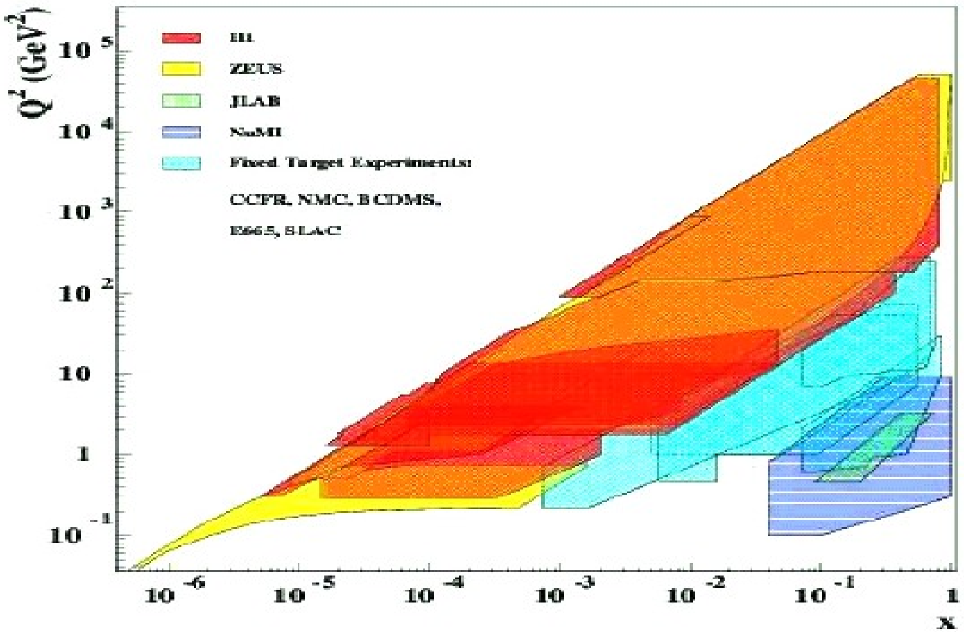
- At higher energies: recent NuTeV precision structure functions measurements, with neutrinos and antineutrinos on Fe

(Source: M. Tzanov, NuFact06)

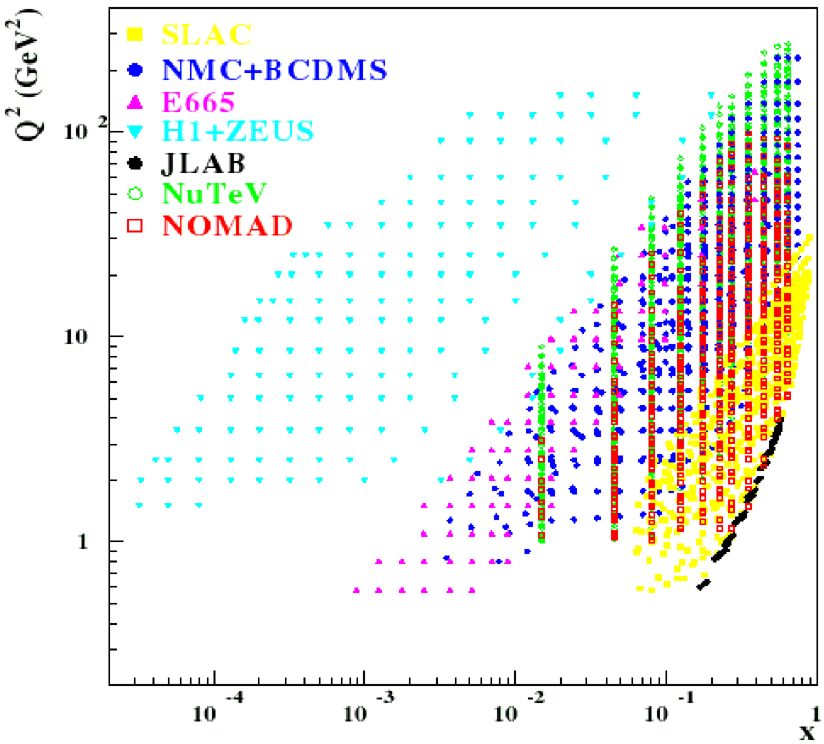


Summary of Transition Region Progress Since NuInt01

MINOS and NOMAD: able to cover regions of phase space (high x, low/medium Q^2) for structure functions measurements that are complementary to charged lepton scattering and beyond past neutrino scattering experiments. Relevant for relatively low energy neutrino beams



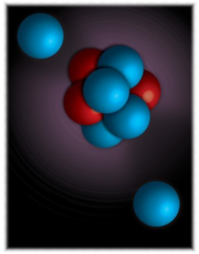
(Source: D. Naples, APS-DPF 2006)



(Source: R. Petti, NuInt05)

- Look forward to new NuInt07 transition region/DIS results (Sessions 6 and8):
  - C. Mariani, *"Neutral Pion Production Cross Sections at K2K"*
  - D. Naples, *"NuTeV Structure Function Measurements"*

Nuclear Effects



- *Fermi motion and binding energy of target nucleons*
-> changes interaction kinematics

- *Pauli suppression of the phase space available to final state nucleons*
-> causes Q^2-dependent suppression of the cross-sections

- *Final state interactions (FSI) inside the nucleus, such as proton re-scattering or pion absorption*
-> can change composition and kinematics of the hadronic part of the final state

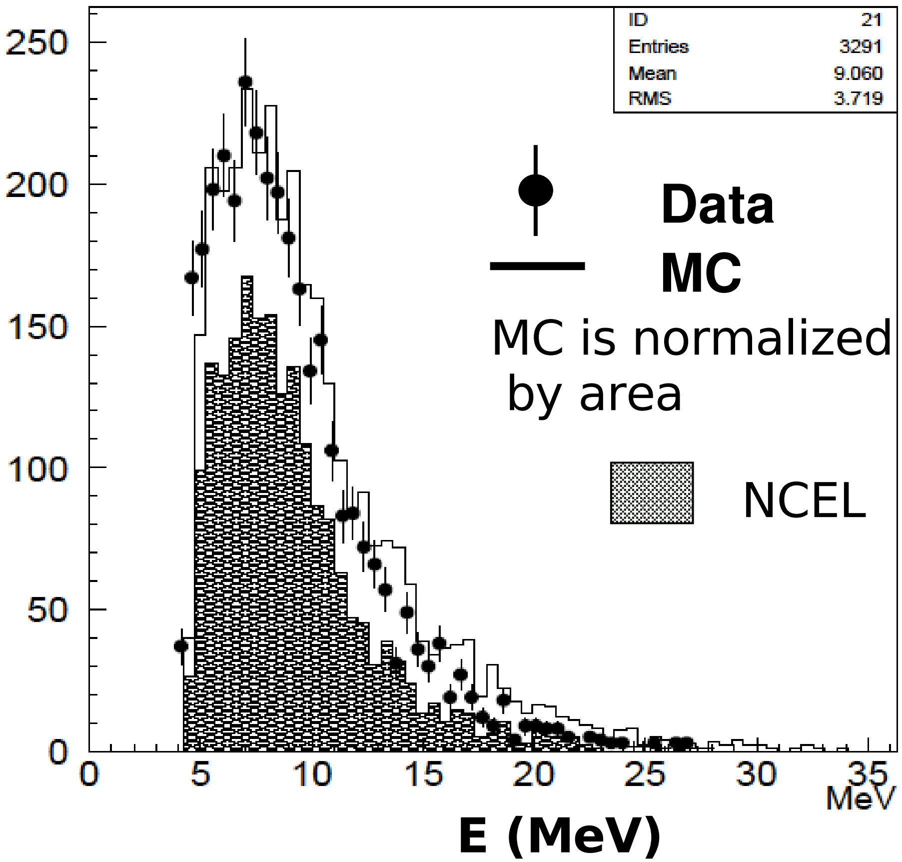
- Effect of Fermi motion and Pauli suppression generally simulated according to simple zero-temperature *relativistic Fermi gas model* for the target neutrons and protons, Various choices for FSI treatment,tuned on π/p data

- Depending on energy thresholds and nuclei, understanding nuclear de-excitation via gamma ray emission may also be needed

Nuclear De-excitation in K2K-1KT

- ~40% of neutrino interactions off a nucleon in oxygen accompanied by ~6 MeV gamma ray emission from nuclear de-excitation

- Allows to study $\nu_\mu N \rightarrow \nu_\mu N$ scattering (NCEL) in water Cerenkov detector
- Select ~3,000 gamma candidate events by requiring low PMT hit multiplicity, containment, single Cherenkov track hit topology. Estimated NCEL purity: ~58%



- 6 MeV peak clearly seen with neutrinos
- After correcting for multi-interactions per spill:

N(data)/N(MC) = 1.23 ± 0.04 ± 0.06 (detector systematics only)

- MC prediction is normalized with respect to CC inclusive measurement

(Source: J. Kameda, NuInt05)

MiniBooNE+K2K Low-Q2 Interactions

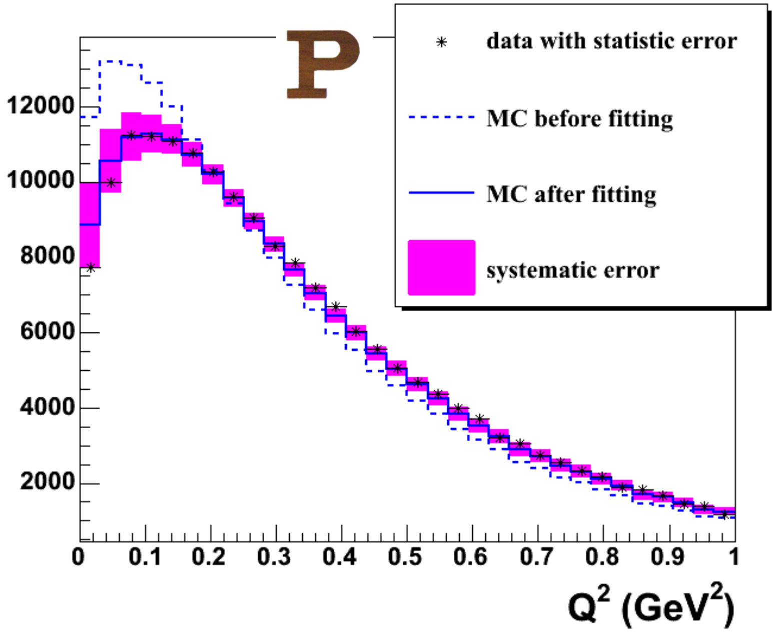
- Low-Q^2 interactions: mostly affected by nuclear effects, *e.g.* Pauli suppression
- Early analyses of various low-Q^2 samples at both MiniBooNE and K2K showed a deficit with respect to predictions for $Q^2 < 0.2$ GeV^2
- Experiments have followed distinct approaches to tune low-Q^2 predictions

- *MiniBooNE:* introduce extra degree of freedom in relativistic Fermi gas model to control strength of Pauli suppression

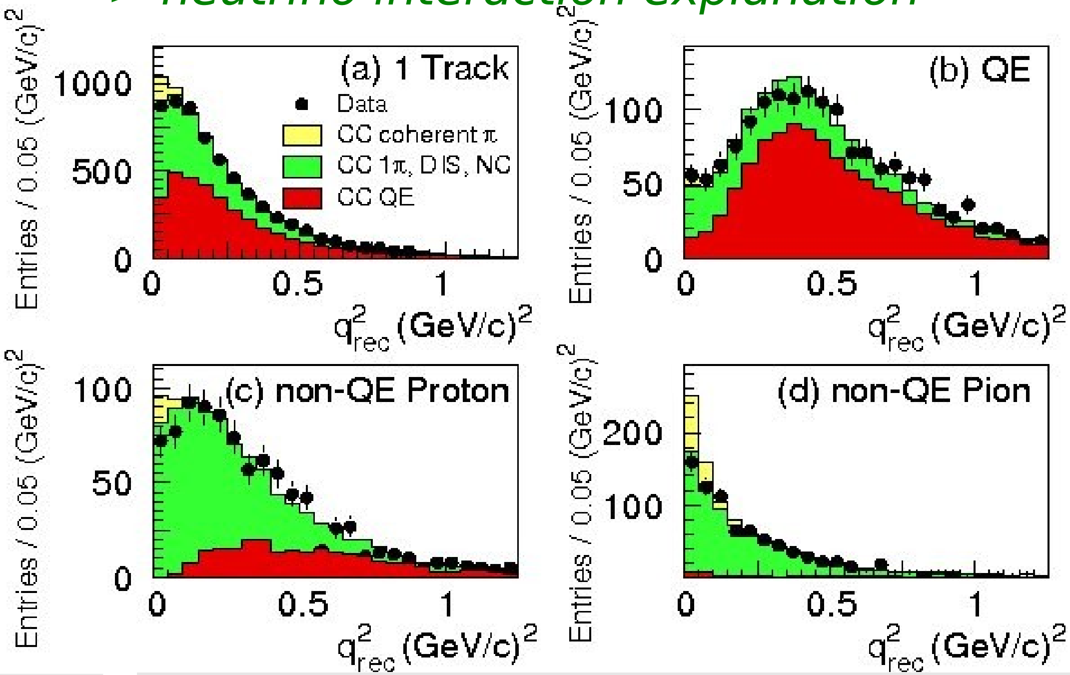
-> nuclear physics explanation

- *K2K*: most (if not all) of the discrepancy goes away by assuming no coherent pion production

-> neutrino interaction explanation



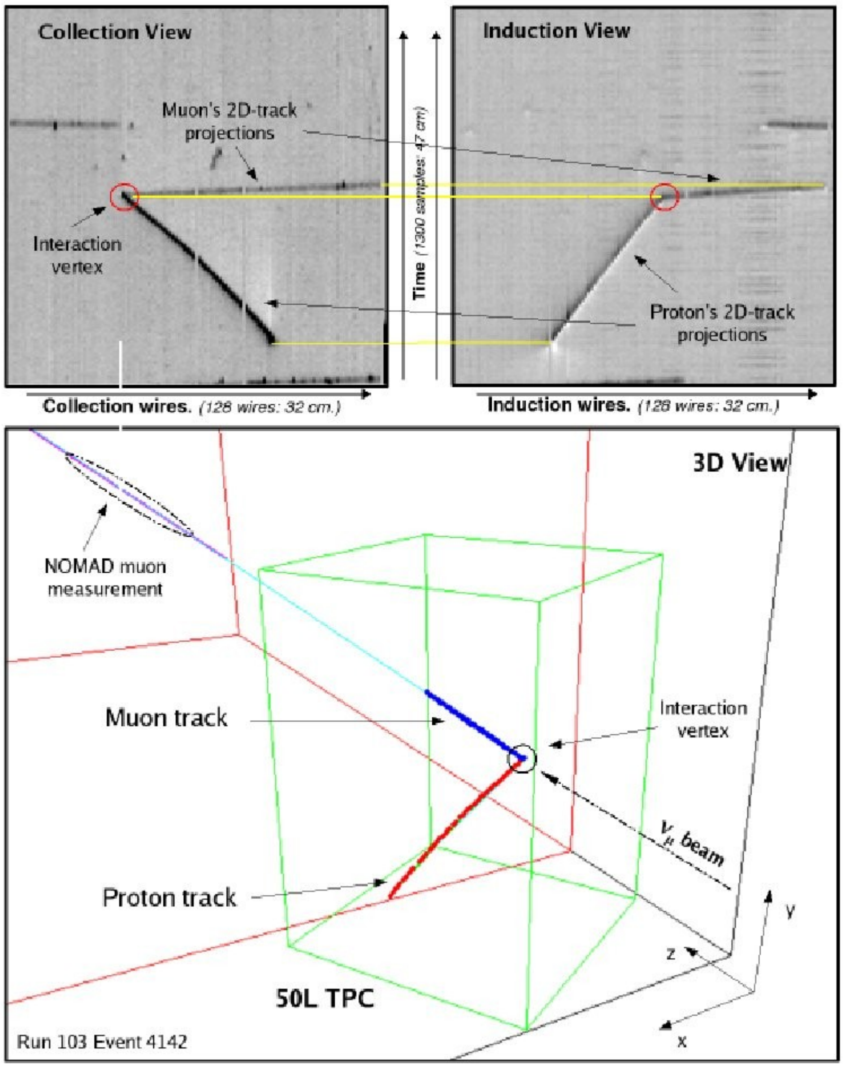
(Source: J. Conrad, B. Louis, FNAL Seminar, 2007)



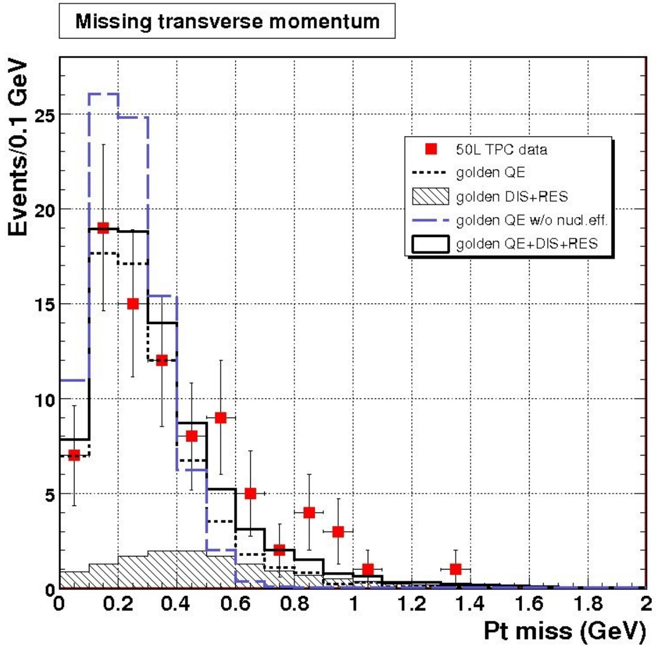
(Source: Phys. Rev.Lett. 95, 252301 (2005))

Nuclear Effects in LAr50

- Expose 50 lt. LAr TPC to CERN multi-GeV wide-band beam, using NOMAD as muon spectrometer



- Select “golden” *CCQE sample* of 86 events with ~80% estimated purity
- *Missing transverse momentum* sensitive to Fermi motion, proton re-scattering and pion absorption inside the nucleus
- Clear evidence seen for nuclear effects beyond Fermi motion and Pauli suppression



(Source: Phys. Rev. D74, 112001 (2006))

Nuclear Effects Progress Since NuInt01

• Experiments got not only better at correcting for nuclear effects, but also at trying to *quantitatively* evaluate associated uncertainties. Mostly new since NuInt01. Some examples below on nuclear effects uncertainties in recent analyses:

Experiment	Quantity	Status	Approx. uncertainty from Fermi gas model	Approx. uncertainty from nuclear FSI
K2K-SciFi	CCQE M_A $(Q^2 > 0.2\ \mathrm{GeV}^2)$	published	-	$\pm 3\%$
K2K-SciFi	CCQE M_A $(Q^2 > 0)$	published	$\pm 5\%$	$\pm 3\%$
K2K-1KT	$\sigma(\mathrm{NC}\pi^0)/\sigma(\mathrm{CC})$	published	-	$\pm 2\%$
MiniBooNE	$\sigma(\mathrm{NC}\pi^0)$	preliminary	$\pm 15\%$	$\pm 15\%$
MiniBooNE	$\sigma(\mathrm{CC}\pi^+)/\sigma(\mathrm{CCQE})$	preliminary	$\pm 5\%$	$\pm 5\%$
K2K-SciBar	$\sigma(\mathrm{CC\ coh}\ \pi)/\sigma(\mathrm{CC})$	published	-	$\pm 0.2\%$ (abs.)
MiniBooNE	$\sigma(\mathrm{NC\ coh}\ \pi)/\sigma(\mathrm{NC}\pi^0)$	preliminary	$< \pm 8\%$	$< \pm 3\%$

• Tendency to be conservative, also to cover possible model deficiencies (e.g. relativistic Fermi gas model)

• Look forward to new NuInt07 nuclear effects results with neutrinos (Sessions 5,9):
  - T. Katori, *“Charged-Current Interaction Measurements in MiniBooNE”*
  - A. Curioni, *“Neutrino Interactions in LArTPCs”*

Summary

Review progress in neutrino scattering measurements since NuInt01:

- Several new cross section results, spanning all relevant channels (CCQE, RES, COH, DIS), and including study of nuclear effects with neutrinos
- Samples of higher statistics allow for more detailed differential cross sections as well
- Large error bars may be deceiving, but tend to represent more accurately current systematic uncertainties affecting the measurements, with respect to what was done in the past
- Nevertheless, recent results not always consistent with each other and with past ones, pointing to either non-understood experimental biases, or deficiencies in the models used to analyze the data. Need to solve this to get to the precision era in few-GeV neutrino-nucleus scattering

The future is bright:

- NuSNS, SciBooNE, T2K Near, MINERvA, MINOS Near, NovA Near,... (Session 3)
- Synergies established with nuclear physics, charged lepton DIS and theory communities